National Aeronautics and
Space Administration

NOT MEASUREMENT SENSITIVE

NASA-STD-5001
JUNE 21, 1996

STRUCTURAL DESIGN AND TEST FACTORS OF SAFETY FOR SPACEFLIGHT HARDWARE

NASA TECHNICAL STANDARD

FOREWORD

This standard is approved for use by NASA Headquarters and all Field Centers and is intended to provide a common framework for consistent practices across NASA programs.

The material covered in this standard is based on the consensus judgment of a working group of structural engineers from all the NASA Centers. The group was empowered by the NASA Engineering Management Council (EMC) to develop more uniform design and verification criteria to be applicable NASA wide. This activity was prompted by concerns expressed by industry and NASA program management that practices and requirements in this area vary widely between Centers, making the verification of structural adequacy difficult in cases involving multiple Centers, and increasing costs to verify identical hardware under different criteria.

Requests for information, corrections, or additions to this standard should be directed to the Structures and Dynamics Laboratory, Mail Code ED21, Marshall Space Flight Center, AL, 35812. Requests for additional copies of this standard should be sent to NASA Engineering Standards, EL02, MSFC, AL, 35812 (telephone 205-544-2448).

Daniel R. Mulville
Chief Engineer

This Page Left Blank Intentionally

CONTENTS

CONTENTS (Continued)

TABLES

STRUCTURAL DESIGN AND TEST FACTORS OF SAFETY FOR SPACEFLIGHT HARDWARE

1. SCOPE

1.1 Purpose. This standard establishes structural strength design and test factors, as well as service life factors to be used for spaceflight hardware development and verification. It is intended to reduce space project costs and schedules by enhancing the commonalty of use of hardware designs between NASA flight projects, Centers, and their contractors. While it is true that structural designs are sometimes governed by criteria other than strength, the criteria in this document are to be considered as minimum acceptable values unless adequate engineering risk assessment is provided which justifies the use of lower values.

1.2 Applicability. This standard recommends engineering practices for NASA programs and projects. It may be cited in contracts and program documents as a technical requirement or as a reference for guidance. Determining the suitability of this standard and its provisions is the responsibility of program/project management and the performing organization. Individual provisions of this standard may be tailored (i.e., modified or deleted) by contract or program specifications to meet specific program/project needs and constraints. Where this document is adopted or imposed by contract on a program or project, the technical guidelines of this document take precedence, in the case of conflict, over the technical guidelines cited in other referenced documents. Project specific tailoring may generate other project specific requirements that are derivatives of this standard. This document shall not supersede applicable laws and regulations unless a specific exemption has been obtained.

The criteria in this standard are applicable to launch vehicles, including their propellant tanks and solid rocket motor cases, and payloads. These criteria apply to flight hardware which is utilized for NASA missions. The standard presents acceptable minimum factors of safety for use in analytical assessment and test verification of structural adequacy of the flight hardware. Designs must generally be verified by both structural strength analyses and tests. The factors are to be multiplied by the limit stresses (including additive thermal stresses), and the products must be verified not to exceed material allowable stresses (yield and ultimate) under the expected temperatures and other operating conditions.

Criteria are specified for design and test of flight articles where the actual flight hardware is tested (protoflight), and where qualification tests are conducted on a separate (prototype) article. In general, no distinction is made between “manned” and “unmanned” missions. Structures of manned flight systems may be subjected to additional verification and/or safety requirements (e.g., fracture control) that are consistent with the established risk levels for mission success and flight crew safety.

The requirements specifically excluded from this standard are: design loads determination, fracture control, pressure vessels, pressurized components, engines, rotating hardware, solid propellant, insulation, ground support equipment, and facilities. Also excluded are specific configuration factors, such as fitting factors, buckling knockdown factors, and load uncertainty factors.

1.3 Constraints and preconditions. The criteria of this standard were developed in the context of structural and mechanical systems designs which are amenable to engineering analyses by current state-of-the-art methods and conforming to standard aerospace industry practices. More specifically, the designs are assumed to use materials having mechanical properties that are well characterized for the intended service environments and all design conditions. For reusable and multi-mission hardware, these criteria are applicable throughout the design service life and all of the missions. Therefore, design considerations must include material property degradation under the service environments. Material allowables shall be chosen to minimize the probability of structural failure due to material variability. Allowables shall be based on sufficient material tests to establish values on a statistical basis. Further, the service environments and limit loads shall be well defined, and aerospace standard manufacturing and process controls shall be used in the hardware fabrication and handling. Test hardware shall be representative of the flight configuration.

2. APPLICABLE DOCUMENTS

There are no applicable documents cited for this standard.

3. DEFINITIONS

3.1 Acceptance test. A test performed on each article of the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, acceptance, proof, and protoflight tests are synonymous.

3.2 Creep. Time-dependent permanent deformation under sustained load and environmental conditions.

3.3 Detrimental yielding. Yielding that adversely affects the fit, form, function, or integrity of the structure.

3.4 Factors of safety (safety factors). Multiplying factors to be applied to limit loads or stresses for purposes of analytical assessment (design factors) or test verification (test factors) of design adequacy in strength or stability.

3.5 Failure. Rupture, collapse, excessive deformation, or any other phenomenon resulting in the inability of a structure to sustain specified loads, pressures, and environments, or to function as designed.

3.6 Fatigue. The cumulative irreversible damage incurred in materials caused by cyclic application of stresses and environments resulting in degradation of load carrying capability.

3.7 Limit load. The maximum anticipated load, or combination of loads, which a structure may experience during its service life under all expected conditions of operation or use.

3.8 Maximum design pressure (MDP). The highest possible operating pressure considering maximum temperature, maximum relief pressure, maximum regulator pressure, and, where applicable, transient pressure excursions. MDP for Space Shuttle payloads is a two-failure tolerant pressure, i.e., will accommodate any combination of two credible failures that will affect pressure during association with the Space Shuttle. MDP also accommodates the maximum temperature to be experienced in the event of an abort to a site without cooling facilities.

3.9 Pressure vessel. A container designed primarily for storing pressurized gases or liquids and (1) contains stored energy of 14,240 foot-pounds (19,309 Joules) or greater, based on adiabatic expansion of a perfect gas; or (2) experiences a limit pressure greater than 100 pounds per square inch absolute (psia) (689.5 kiloPascal [kPa] absolute); or (3) contains a pressurized fluid in excess of 15 psia (103.4 kPa absolute), which will create a safety hazard if released.

3.10 Pressurized component. A line, fitting, valve, or other part designed to contain pressure and that (1) is not made of glass, or (2) is not a pressure vessel, or (3) is not a propellant tank, or (4) is not a solid rocket motor case.

3.11 Proof test. A test performed on the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, proof, acceptance, and protoflight tests are synonymous.

3.12 Proof test factor. A multiplying factor to be applied to the limit load or MDP to define the proof test load or pressure.

3.13 Protoflight test. A test performed on the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, protoflight, acceptance, and proof tests are synonymous.

3.14 Prototype test. A test performed on a separate flight-like structural test article to verify structural integrity of the design. Prototype tests and qualification tests are synonymous.

3.15 Qualification test. A test performed on a separate flight-like structural article of each type to verify structural integrity of the design. Qualification and prototype tests are synonymous.

3.16 Qualification test factor. A multiplying factor to be applied to the limit load or MDP to define the qualification test load or pressure.

3.17 Safety critical. A classification for structures, components, procedures, etc., whose failure to perform as designed or produce the intended results would pose a threat of serious personal injury or loss of life.

3.18 Service life. All significant loading cycles or events during the period beginning with manufacture of a component and ending with completion of its specified use. Testing, transportation, lift-off, ascent, on-orbit operations, descent, landing and post-landing events shall be considered.

3.19 Service life factor (life factor). A multiplying factor to be applied to the maximum expected number of load cycles in the service life to determine the design adequacy in fatigue or fracture.

3.20 Ultimate design load. The product of the ultimate factor of safety and the limit load.

3.21 Ultimate strength. The maximum load or stress that a structure or material can withstand without incurring failure.

3.22 Yield design load. The product of the yield factor of safety and the limit load.

3.23 Yield strength. The maximum load or stress that a structure or material can withstand without incurring detrimental yielding.

4. GENERAL REQUIREMENTS

4.1 Selection criteria for factors of safety. The appropriate design and test factors for a given mechanical or structural flight hardware element depend on several parameters such as the materials used, attachment methods (e.g., bonding), and the verification approach (prototype or protoflight). In applying the minimum factors of safety specified in this standard, it must be recognized that some structural and mechanical members and systems may be required to meet other more stringent and restrictive performance requirements such as dimensional stability, pointing accuracy, stiffness/frequency constraints, or safety requirements (e.g., fracture control).

4.1.1 Prototype versus protoflight approaches. The standard accepted practice for verification of launch vehicles is the prototype approach in which a separate, dedicated test structure, identical to the flight structure, is tested to demonstrate that the design meets the factor of safety requirements.

A widely used acceptable alternative for verification of spacecraft and science payloads is the protoflight approach, wherein the flight structure is tested to levels somewhat above limit stress (or load) but below yield strength. In order to preclude detrimental yielding during protoflight strength verification testing, the yield factor of safety for protoflight structural design must be higher than the test factor. The protoflight test shall be followed by inspection and functionality assessment.

Consideration shall be given to development test prior to committing to major test article configurations and especially prior to committing the flight article to protoflight test.

4.1.2 Test verification criteria.

4.1.2.1 Test methods. Strength verification tests fall into three basic categories: tests to verify strength of the design (qualification, acceptance, or proof), tests to verify strength models, and tests to verify workmanship and material quality of flight articles (acceptance or proof).

Strength verification tests are normally static load tests covering all critical load conditions in the three orthogonal axes and, generally, can be classified as prototype or protoflight (see 4.1.1). The magnitude of the static test loads should be equivalent to limit loads multiplied by the qualification, acceptance, or proof test factor. In some cases, alternative test approaches (centrifuge, below resonance sine burst, saw tooth shock, etc.) are more effective in reproducing the critical load or environmental conditions and may be used in lieu of static testing if it can be demonstrated that the resulting loads in the test article are equivalent to or larger than the limit loads multiplied by the test factor.

Strength model verification tests are normally done as part of the strength verification tests. Model verification must be accomplished over the entire load range. The test article must be adequately instrumented to provide sufficient test data for correlation with the strength model. Workmanship tests may be static or dynamic load tests. Dynamic tests may be sinusoidal vibration, random vibration, or acoustic. Test loads should be equivalent to or slightly higher than the limit loads. Each propellant tank and each solid rocket motor case shall be proof pressure tested.

4.1.2.2 Test versus design factors of safety. When using the prototype structural verification approach, the minimum ultimate design factors can be the same as the required qualification test factors for both metallic and composite/bonded structures. Metallic structures should be verified to have no detrimental yielding at yield design load before testing to full qualification load levels.

When using the protoflight structural verification approach, design factors larger than the required acceptance or proof test factors shall be used to prevent detrimental yielding of the metallic or damage to the composite/bonded flight structure during test.

4.1.2.3 Test versus no-test options. Structural designs generally should be verified by analysis and by either prototype or protoflight strength testing. Under some circumstances, it may be permissible to verify structural integrity by analysis alone without strength testing, provided an acceptable engineering rationale is developed. Increasing the design factors of safety does not by itself justify this “no-test” approach. Some examples of criteria on which to base such an approach are:

a. The structural design is simple (e.g., statically determinate) with easily-determined load paths, it has been thoroughly analyzed for all critical load conditions, and there is a high confidence in the magnitude of all significant loading events.

b. The structure is similar in overall configuration, design detail, and critical load conditions to a previous structure which was successfully test verified, with good correlation of test results to analytical predictions.

c. Development and/or component tests have been successfully completed on critical, difficult to analyze elements of the structure. Good analytical model correlation to test results has been demonstrated.

Standard criteria cannot be specified for general use in designing structures for which no verification tests are planned. Projects which propose to use the “no-test” approach generally must use larger factors of safety and develop project-specific criteria and rationale for review and approval by the responsible NASA Center. For spacecraft and other payloads launched on the Space Shuttle, these criteria must also be approved by the Space Shuttle Payload Safety Review Panel prior to their implementation.

4.1.3 Probabilistic methods. Design factors of safety and test factors are intended to conservatively compensate for uncertainties in the strength analysis. Current standard NASA structural verification criteria are deterministic, and experience has shown these deterministic criteria to be adequate. The probabilistic method uses knowledge (or assumptions) of the statistical variability of the design variables to select design criteria for achieving an overall success confidence level. Any proposed use of probabilistic criteria to supplement deterministic factors of safety shall be approved by the responsible NASA Center on an individual case basis.

5. DETAILED REQUIREMENTS

5.1 Design and test factors of safety. The design factors of safety and test factors of this standard are the minimum required values for NASA spaceflight structures and shall be applied to both mechanical and additive thermal stresses. Applications of these factors to the development and verification of a structure will be accepted by the responsible NASA Center only when all of the constraints and preconditions specified in 1.3 are met. Higher factors than those listed here may be required for proof testing if the proof test is to be used for fracture control flaw screening. If pressure or temperature has a relieving or stabilizing effect on the mode of failure, then for analysis or test of that failure mode, the unfactored stresses induced by temperature or the minimum expected pressure shall be used in conjunction with the ultimate (factored) stresses from all other loads. Otherwise, the design and test factors shall be applied equally to MDP and other stresses.

Factors of safety on yield are not specified for fasteners, composite/bonded structures, glass, and bonds for structural glass. These hardware items shall be designed to preclude any detrimental permanent deformation or functional degradation of the flight system under the limit loads and, for programs employing the protoflight verification approach, the acceptance or proof test loads.

5.1.1 Metallic structures. Spaceflight metallic structures may be developed using either the prototype or the protoflight approach. The minimum design and test factors of safety for metallic structures, excluding fasteners, are specified in Table I.

TABLE I. Minimum Design and Test Factors for Metallic Structures

Verification Approach	Ultimate Design Factor	Yield Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	1.4	1.0*	1.4	NA or 1.05**
Protoflight	1.4	1.25	NA	1.2

NOTES:
* Structure must be assessed to prevent detrimental yielding during flight, acceptance, or proof testing.
** Propellant tanks and solid rocket motor cases only.

5.1.2 Fasteners and preloaded joints. The minimum design and test factors for fasteners shall be as specified in Table II. The strength of fasteners used in preloaded joints shall be assessed at zero and maximum preload. For the zero preload case, the factor of safety shall be applied to the induced fastener load. For the maximum preload case, the factor of safety need only be applied to the additional fastener load induced beyond the preload. In both cases, the preload plus induced fastener loads times the factor of safety shall be less than the fastener ultimate strength. Unless specifically designed to separate, all joints shall maintain a factor of safety against separation. Minimum preload shall be used in the separation assessment.

TABLE II. Minimum Design and Test Factors for Fasteners and Preloaded Joints

Verification Approach	Design Factors			Test Factors	
	Ultimate Strength	Joint Separation		Qualification	Acceptance or Proof
		Safety Critical *	Other		
Prototype	1.4	1.4	1.2	1.4	NA
Protoflight	1.4	1.4	1.2	NA	1.2

NOTE:
* Joints that maintain pressures and/or hazardous materials in a safety-critical application.

5.1.3 Composite/bonded structures. Composite/bonded structures, excluding glass, developed for NASA spaceflight missions shall, as a minimum, use the design and test factors specified in Table III. Each flight article under the composite/bonded prototype approach requires acceptance or proof testing unless the requirements of 4.1.2.3 or 5.3 are met.

TABLE III. Minimum Design and Test Factors for Composite/Bonded Structures

Verification Approach	Geometry of Structure	Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	Discontinuities	2.0*	1.4	1.05
	Uniform Material	1.4	1.4	1.05
Protoflight	Discontinuities	2.0*	NA	1.2
	Uniform Material	1.5	NA	1.2

NOTE:
* Factor applies to concentrated stresses. For non-safety critical applications, this factor may be reduced to 1.4 for prototype structures and 1.5 for protoflight structures.

5.1.4 Glass. The minimum design and test factors for pressurized and nonpressurized glass shall be as specified in Table IV. Structural integrity of all pressurized glass shall be verified by both analysis and testing. Nonpressurized glass may be verified by analysis only with an ultimate minimum design safety factor of 5.0. The prototype verification option is not available for glass. Protoflight tests of glass shall be configured to simulate flight-like boundary conditions and loading. For glass protoflight testing, the total time during load, dwell, and unload shall be as short as possible and shall be done in an inert environment to minimize flaw growth. Care should also be taken to configure protoflight hardware to prevent overloading any bonded joints during test.

TABLE IV. Minimum Design and Test Factors for Glass

Verification Approach	Loading Condition	Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Protoflight	Nonpressurized	3.0	NA	1.2
	Pressurized	3.0	NA	2.0
Analysis Only	Nonpressurized	5.0	NA	NA

5.1.5 Bonds for structural glass. Bonds for structural glass shall be qualification tested on a separate article, and each flight article shall be proof tested. The design and test factors are specified in Table V.

TABLE V. Minimum Design and Test Factors for Structural Glass Bonds

Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
2.0	1.4	1.2

5.2 Fatigue and creep. For NASA spaceflight structures made of well-characterized materials and with sufficient load cycle data that accounts for all in-service environments, a minimum service life factor of 4.0 shall be applied to the service life for fatigue and creep life assessments.

5.3 Alternate approaches. In the event a particular factor of safety requirement of this standard cannot be met for a specific spaceflight structure or hardware component, an alternative or modified approach shall be proposed to verify the strength adequacy of the design. A written risk assessment that justifies the use of the alternate approach must be prepared by the organization with primary responsibility for the development of the structure or component. The risk assessment shall be submitted to the responsible NASA Center for approval prior to the implementation of the alternative approach.

6. NOTES

(This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.)

6.1 Key word listing:

Acceptance test
Factors of safety
Proof test
Protoflight test
Prototype test
Qualification test
Spaceflight hardware
Standard
Structural design criteria
Test factors
Verification